Technological Decision to Renewable Energy Usage Biogas for Off-grid Systems Consumption

Marina Zubkova[1,*], *Vladimir* Maslikov[1], *Dmitry* Molodtsov[1], *Alexander* Chusov[1], *Viacheslav* Zhazhkov[1], and *Alexander* Stroganov[2]

[1]Peter the Great St.Petersburg Polytechnic University, 195251, Polytechnicheskaya st. 29, St. Petersburg, Russia
[2]Lumex Instruments Canada, Unit 207, 31510 Gill Avenue, Mission, B.C., V4S0A1 Canada

Abstract. This paper presents the results of the energy experiments based on electrochemical researches and the thermodynamic calculations, which are carried out on the hydrogenous fuel with the residual content of methane obtained from biogas selected organic waste. Energy indicators are examined in comparison to electrolysis hydrogen. The use of technical and electro physical indicators together with parameters of the fuel operating allowed assessing energy efficiency the module reformer - fuel cell running on a non-standard hydrogenous fuel. Numerical characteristic the efficiency of workflows fuel system reformer – fuel cell is about 39%. To operate the power installation with a predetermined capacity amount used of hydrogenous fuel is comparable to required electrolysis hydrogen amount. Shown the possibility of creation the systems of power supply based on new hydrogen technologies using renewable energy resources local waste. Confirms the relatively high efficiency the usage of hydrogenous fuel for the tasks of off-grid systems consumption.

1 Introduction

One of the most important directions of energy saving is creation of autonomous and economic systems of electric power supply of the consumers, allowing to receive electric and thermal energy in a place of its consumption for decrease in losses and increase reliability of energy supply [1]. It is promising to use for the purpose of fuel cells, offering a direct conversion of the energy of the fuel into electrical energy [2-4]. They are characterized by high energy- economic indicators, reliable performance, quiet operation, mobility, lack of harmful emissions, etc. Fuel cells can be used as stationary and emergency backup power supply in autonomous systems [3-7]. For loads from a few kilowatts to several hundred kilowatts (consumers in a low housing estate) it is preferred application of low-temperature fuel cells that run on hydrogen.

In the European Union countries, the USA, Japan, etc. works on receiving hydrogen from biogases and its use in energy supply of autonomous consumers. Identified

[*] Corresponding author: marina19zubkova@list.ru

weaknesses of installations - the low content of hydrogen in the reformate (70-80% vol.) and existence in it harmful impurity. It demands use of expensive and difficult systems in operation of its cleaning that leads to increased power consumption and reduced process effectiveness. Therefore, it is urgent is the development of technologies for producing biogas from relatively cheap enough "clean" hydrogen and methods of its direct use in low-temperature hydrogen fuel cells [7-11].

Efficiency of operation the autonomous system with fuel cells in many respects will be defined by the cost of receiving hydrogen. The cheapest way by far is the production of hydrogen from natural gas. The hydrogen received from biogas of agricultural waste is rather cheap. In the long term, it is necessary to expect increase of cost of natural gas owing to what production of hydrogen from biogas can be cheaper, than from natural gas [11-14].

The task to determine the possibility of using hydrogenous fuel with residual methane content in fuel cells, and carrying out the calculations for assessing the energy efficiency of non-standard fuel, gives the opportunity fundamentally changed the approach to technologies considering secondary sources [10, 12-14].

Biogas can be obtained practically everywhere as organic-containing waste is constantly formed in the course of economic activity of the person, meanwhile resources of natural gas are limited, and its use is limited. There is a unique possibility of creation of systems of energy supply of autonomous consumers based on the new hydrogen technologies using as an energy resource local waste [8, 11-15].

In Peter the Great St. Petersburg Polytechnic University experimental system for studying the processes of obtaining and using biogas consisting of biogas generating modules, its accumulation and purification, methane reforming to hydrogen production is created [11]. Stable hydrogen production of high purity (98.5% vol.) is experimentally confirmed at biomethane supply (about 95%) in the wide range of loadings of a reformer (30-100% from nominal) [12,13]. In a reformer there is an internal utilization of CO_2, and its contents in reformate also does not exceed 10 ppm. The experiments on the use of "weak" biogas containing methane 30-45 % vol. were also carried out [14-16]. The concentration of hydrogen in the reformate remains high (more than 93% vol.) [12]. This extends the use of the considerable potential "weak" biogas with a relatively low concentration of organic components for autonomous power engineering in the direct use of hydrogen-derived fuels in the energy system to produce electricity and heat. Testing of a fuel element during multiple cycles (supplying-reset) allows to define its energy efficiency and optimum operating modes and to estimate opportunity and efficiency of use of hydrogen fuel with the methane component, received from biogases by two-steps conversion, in a low-temperature fuel cell

Principle possibility of the fuel cell operation on gas mixture with methane not oxidizing on the anode [12,15,16] and formation of a stream of purge of methane-hydrogenous mixture is confirmed. Modes of return of the fuel cell to the baseline characteristics after steady work for a non-standard hydrogenous fuel are fulfilled [14-18].

2 Experimental studies

We set the task based on the experimental results, the data of the material balance and thermodynamic evaluations on the effectiveness of the use of non-standard hydrogenous fuel, carry out the model calculation of fuel consumption derived from biogas required for the efficient operation of the unit conversion fuel – "reformer-fuel cell" to meet the optimal resource capacity and the time duration.

The studies were carried out using the unique scientific unit "The laboratory complex for study of processes for obtaining and converting biogas from organic waste" in Peter the Great St.Petersburg Polytechnic University.

Experimental studies were carried out on a special stand [11] in the mode of direct supply of hydrogenous fuel to the fuel cell with parallel testing of the fuel cell on hydrogen and oxygen obtained by electrolysis, which allows to make comparisons of the electrochemical characteristics of the oxidation the fuel and the number of purges of unfinished fuel [11-17].

Results of experiments at step change of the set potential on the fuel module FC-50 (dead end) with connection of purge system for unfinished fuel from the anode of a fuel cell for hydrogen obtaining by electrolysis (mode 1) and non-standard hydrogenous fuel (mode 2) are presented in Fig. 1. As an oxidizer air oxygen with a necessary excess expense was used. Excessive pressure of fuel supply on a cell maintained within the limits 0.9 bar. Analysis of plots (Fig. 1) shows that when running on electrolysis hydrogen, fuel purges does not occur on the interval considered a step change in capacity. Consequently, the fuel feeding rate and the resulting number of protons at the anode sufficient to maintaining a stable electrochemical process in the fuel cell. For a hydrogen fuel gas mixture purges occur at high current (or power) as not discharged molecules of CH_4 interferes with access of necessary amount of hydrogen to a catalytic surface of the anode.

Characteristics of studies for modes 1 and 2 are shown in Table 1.

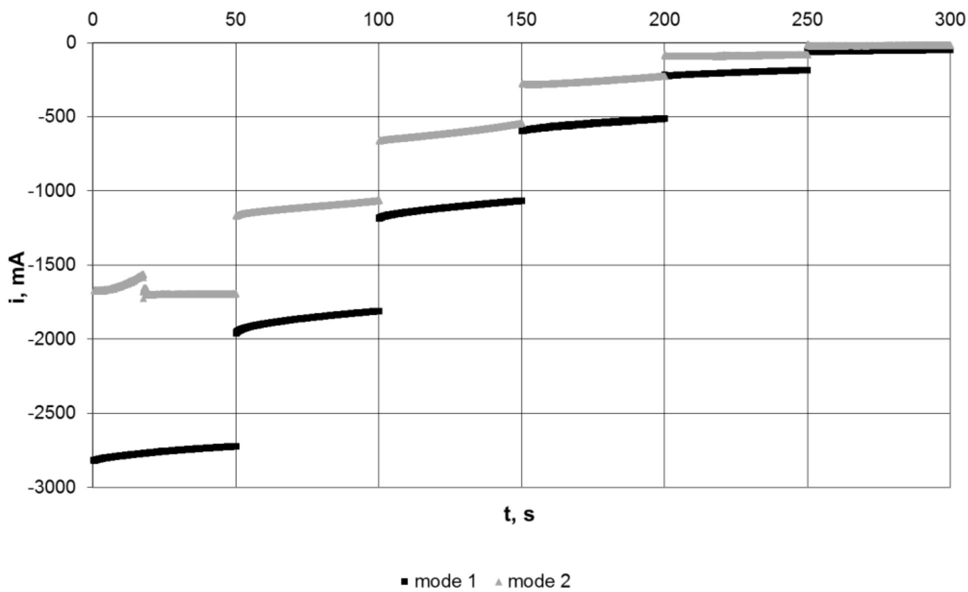

Fig. 1. The change of current over time at step change of potential. Mode 1: H2/air, P= 0.9 bar; mode 2: hydrogenous fuel/air, P=0.9 bar.

It should be noted that the amount of gas consumed per unit of produced electricity and power comparable to study modes. This confirms the ability effectively module work on hydrogenous fuel derived from biogas, and achieving fuel-efficient modes.

Joint analysis of plots (Fig. 2) and in Table 2 suggests that while working on electrolysis hydrogen fuel discharge does not occur on the considering duration the fuel cell operation. Consequently, the fuel feeding rate and the resulting number of protons at the anode sufficient to sustain a stable electrochemical process in the fuel cell. For a gas mixture of CH_4 fuel discharges occur at high current (or power) as not discharged molecules CH_4 prevent access required amount of hydrogen to the catalytic surface of the anode. Increasing the excess fuel pressure reduces the number of purges due to increased fuel supply rate, that is, increase the importance of mass transfer stages providing delivery of H_2 to the catalyst surface, and thus to quantity of the particles which are discharged on the anode [17-19].

Table 1. Basic parameters the step change in the potential for module FC-50

E, V	t, s	mode 1 H_2/air, P= 0.9 bar		mode 2, hydrogenous fuel/air, P=0.9 bar	
		V_1, ml	V_2, ml	V_1, ml	V_2, ml
6.0	50	148.3		99.2	
6.5	100	103.3		65.8	
7.0	150	60.8	0	36.7	
7.5	200	31.7		17.5	8.0
8.0	250	13.8		8.3	
8.5	300	6.2		4.6	
		Σ =364.1	purges have not been	Σ = 232.1	1 purge
		Σ= 364.1		Σ = 240.1	

Where:
E – the potential;
t – the time period of step change of potential;
V_1 – the operative volume of the spent gas;
V_2 – gas volume in purges.

The statistical analysis of data shows that on each site of the cycle "work-purge" fall of current and power characteristics at supply of electrolysis hydrogen makes 7%, in case of use of hydrogenous mixture with residual methane falling of these indicators makes 4÷6 of % depending on an operating mode. Use of non-standard fuel demands frequent updating of a surface, i.e. the number of purges for removal from the anode of not oxidized methane molecules together with which also not discharged hydrogen molecules are removed that reduces fall of current and power characteristics. During the work on electrolysis hydrogen purges happen much less often, however fall of these characteristics says that on the anode there is an accumulation of the molecules of hydrogen which aren't discharged to a proton interfering access of again arriving fuel to a catalytic surface.

It should be noted that amount of the spent gas on unit of the made electricity and power are commensurable for all studied modes. It confirms a possibility of effective operation of the module on hydrogenous fuel with the residual content of methane received from biogases and achievements of the modes of effective use of fuel.

Using the relation (1) was determined by the amount of consumed gas for a coulomb electricity (N_q).

$$N_q = \frac{n \cdot G_s \cdot t_s + \Delta t \cdot G_r}{I \cdot t_r}, \quad (1)$$

where:
n – the number of fuel purges on the selected plot of time;
G_s – gas flow rate at the moment purge, ml;
t_s – the time discharge of fuel, s;
Δt – the time interval stable operation of the fuel cell, s;
G_r – flow rate gas to the fuel cell operation, ml;
I – amperage (output characteristic), A;

t_r – the duration the selected area of the fuel cell operation (400 ÷ 1200), s.

The corresponding quantitative indices on considered modes are presented in Table 2.

Table 2. Data of fuel cell operation for fuels of different composition.

mode	fuel	I, A	n	Gs, ml/s	Gr, ml/s	Nq, ml/C
1	H_2	2.0÷2.2	1	12.0	2.5	1.2
2	98% H_2 + 2% CH_4	1.8÷1.9	12	12.0	2.7	1.6

The amount of consumed gas for retrieving 1 coulomb electricity under feeding the electrolysis hydrogen and hydrogen-containing mixture with the residual methane content at an identical oxidizer and pressure of supply of fuel are commensurable. This confirms the possibility of efficient operation of the module on the hydrogenous fuel with a residual methane derived from biogas, and achieving fuel efficiency modes [17-20].

The FC-50 module may be considered as the scale model of more difficult and power-intensive system. The presented results are the basis for calculations for an assessment of overall performance of the 500 W fuel module which can be considered as basic element for off-grid system consumption.

Presented results form the basis of calculations to evaluate the effectiveness of the fuel module 500 W, which can be considered as a basic element for autonomous consumer. The results of estimating calculations the required amount of energy (electrolysis hydrogen and hydrogenous fuel) for the module operation during 2000 hour/year are presented in Table 3.

Table 3. Estimated parameters of necessary expenses energy for operation of the power installation with a capacity of 500 W for t=2000 hours/year

Title indicators	Designation, dimensionality	hydrogen electrolysis	Hydrogenous fuel
Efficiency	η, %	46.3	44.0
Rated Power Energy System	P, kW	0.5	0.5
Power created by the consumable	Pg, kW	1.08	1.01
Electric power generation	W, kW h/year	1000	1000
Mass of fuel consumed	m, kg/year	64.85	75.50

Comparison of the obtained values of mass of fuel consumed to ensure stable operation of the installation within the specified period shows that the consumption of hydrogenous fuel is comparable with the required flow rate of hydrogen electrolysis.

Table 4 shows the results of calculation of the methane and biogas volumes required for obtaining hydrogenous fuel in an amount providing work of the power plant with capacity of 500 W for the module operation during 2000 hour/year.

Table 4. Estimated parameters fuel consumption in the reformer for power installation capacity of 500 W for t=2000 h/year

Title indicators	mass of methane	volume of methane	volume of biogas
Designation, dimensionality	m_{CH4}, kg/year	V_{CH4}, m^3/year	V_{biogas}, m^3/year
Digital value	142.0	197.9	328.0

The efficiency of the tandem system "reformer-fuel power unit" is defined by Eq. 2 [21]. The initial data used normalized values of a tandem system reformer-fuel cell and workflows.

$$\eta_{\Sigma} = \eta_{ref} \cdot \left[2 - u + \left(1 - \frac{1}{\lambda_{H2}} \right) \cdot \eta_{ref} \right] \cdot \frac{1}{\lambda_{H2}} \cdot \frac{U}{u_{ref}}, \tag{2}$$

where:

η_{ref} =0.7 — efficiency of the reformer;

u=0.95 — coefficient of methanization;

λ_{H2} =1.25 — output ratio of hydrogen to one mole of methane;

U=0.720 V — the voltage on the unit cell;

u_{ref} =1.25 V — the reference voltage.

Estimated the effective efficiency of the tandem system based on the reformer with steam reforming of methane and power plant with capacity of 500 W amounted ~ 39 %. This confirms the relatively high efficiency of non-standard hydrogenous fuel use.

3 Conclusions

1. A promising direction in the creation of autonomous power supply systems in low-rise residential development is the use of fuel cells running on hydrogenous fuel derived from biogas.
2. Expenses of hydrogen fuel to operate the power installation with a predetermined capacity comparable with the required amount of hydrogen obtained by electrolysis.
3. The calculated value of the efficiency of the system reformer – fuel cell, based on data on the required quantity of biogas and methane, as well as numerical characteristics of workflows fuel system, nearly to 39 %, confirms the relatively high efficiency of the use of hydrogenous fuel for the tasks of autonomous power supply.
4. Usage of relatively low-cost hydrogen-containing fuel obtained from biogas from local secondary renewable resources will contribute to the creation of autonomous economic systems of power supply.

References

1. N.I. Vatin, D.V. Nemova, D.S. Tarasova, A.A. Staritcyna, Advanced materials research, **953-954**, 854-870 (2014)
2. D.O. Dunikov, V.I. Borzenko, S.P. Malyshenko, D.V. Blinov, A.N. Kazakov, Teploenergetika [Thermal Engineering], **60(3)**, 202-211 (2013)
3. S.P. Malyshenko, V.I. Borzenko, D.O. Dunikov, O.V. Nazarova, Teploenergetika [Thermal Engineering], **59(6)**, 468-478 (2012)
4. G. Gahleitner, International Journal of Hydrogen Energy, **38(5)**, 2039-2061 (2013).
5. K.C. Surendra, D. Takara, A.G. Hashimoto, S.K. Khanal, Renewable and Sustainable Energy Reviews, **31**, 846-859 (2014)
6. J. Havukainen, V. Uusitalo, A. Niskanen, V. Kapustina, M. Horttanainen, Renewable Energy, **66**, 232-240 (2014)
7. R. Chaubey, S. Sahu, O.O. James, S. Maity, Renewable and Sustainable Energy Reviews, **23**, 443-462 (2013)
8. H.J. Alves, C. Bley Junior, R.R. Niklevicz, E.P. Frigo, M.S. Frigo, C.H. Coimbra-Araújo, International Journal of Hydrogen Energy, **38(13)**, 5215-5225 (2013)
9. I. Rodriguez-Verde, L. Regueiro, M. Carballa, A. Hospido, J.M. Lema, Science of the Total Environment, **497**, 475-483 (2014)
10. F. Bauer, T. Persson, C. Hulteberg, D. Tamm, Biofuels, Bioproducts and Biorefining, **7(5)**, 499-511 (2013)

11. M.P. Fedorov, V.I. Maslikov, A.N. Chusov, D.V. Molodtsov, St. Petersburg State Polytechnical University Journal, **4(135)**, 35-41 (2011)
12. M.P. Fedorov, M.Yu. Zubkova, A.A. Thomasov, D.V. Molodtsov, N.K. Zelenina, *Proc. Reports. 7th Russian Conference "Physical Problems of Hydrogen Energy." St. Petersburg: FTI. Joffe*, 160-162 (2011)
13. M.Yu. Zubkova, V.I. Maslikov, D.V. Molodtsov, A.A. Thomasov, *Proc. Report of the Eighth Russian Conference "Physical Problems of Hydrogen Energy", St. Petersburg. FTI. Joffe*, 151-153 (2012)
14. A.N. Chusov, M.Yu. Zubkova, V.V. Korablev, V.I. Maslikov, D.V. Molodtsov, St. Petersburg State Polytechnical University Journal, **4-1(183)**, 78-85 (2013)
15. M.Yu. Zubkova, V.V. Korablev, V.I. Maslikov, D.V. Molodtsov, A.N. Chusov, *Abstracts. International Conference "Innovative materials, Structures and Technologies", Riga. RTU*, 54 (2013)
16. M.P. Fedorov, A.N. Chusov, V.I. Maslikov, M.Yu. Zubkova, D.V. Molodtsov, *Abstracts, VIII International Conference, Fundamental problems of electrochemical energy, Saratov*, 436-439 (2011)
17. M.Yu. Zubkova, V.I. Maslikov, D.V. Molodtsov, A.N. Chusov, Advanced Materials Research, **941-944**, 2107-2111 (2014)
18. M.Yu. Zubkova, V.I. Maslikov, D.V. Molodtsov, A.N. Chusov, Applied Mechanics and Materials, **587-589**, 330-337 (2014)
19. M.Yu. Zubkova, M.P. Fedorov, A.N. Chusov, Innovations, **196(2)**, 70-76 (2015).
20. M.Yu. Zubkova, V.I. Maslikov, M.P. Fedorov, A.N. Chusov, *Proceedings Sardinia 2015, 15-th International Waste and Landfill Symposium, Forte Village, Santa Margherita de Pula, Italy; 5 9 October 2015*, 229 (2015)
21. R. Schmersahl, E. Janine, S. Volkhard, available at: http://brennstoffzellen.pitcom.net/upload/dokument139.pdf (accessed October 05, 2015)